Int J Life Cycle Assess (2011) 16:916–928
DOI 10.1007/s11367-011-0322-6

Life cycle assessment of ceramic tiles. Environmental and statistical analysis

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Received: 7 January 2011 / Accepted: 7 July 2011 / Published online: 4 August 2011

Abstract

Purpose The aim of this paper is to conduct a life cycle assessment study of ceramic tiles (single-fired glazed stoneware) in order to identify the stages that produce the greatest impact on the environment and the materials and/or processes that make the largest contribution to that impact. The life cycle is considered to be made up of seven stages: (1) mining the clay, (2) atomising the clay, (3) production of frits and glazes, (4) production of ceramic tiles, (5) distribution, (6) installation and usage, and, on ending their useful life (7) treatment as construction and demolition waste.

Materials and methods A specific life cycle inventory was developed taking 1 m^2 of ceramic tile over a period of 20 years as the functional unit and using annual data gathered directly from 35 Spanish enterprises involved in the different stages of the life cycle of ceramic tiles. This inventory was then used to obtain environmental indicators (global warming, ozone layer depletion, acidification, eutrophication, photochemical oxidation and human toxicity) for each enterprise and each stage of the life cycle under study.

Results and discussion Environmental data were submitted to a statistical analysis. This analysis made it possible to model the distribution of environmental behaviour of the life cycle of ceramic tiles considering the different influences from the different companies that were consulted for each stage in the life cycle. The statistical study allowed also obtaining confidence intervals for the mean and standard deviation of the environmental results obtained for each impact category.

Conclusions The stage of the life cycle with the greatest environmental impact for all the impact categories is the manufacture of the tile, followed by the process of atomising the clay and the distribution of the product. There is a direct correlation between these findings and the high level of energy consumption (mainly natural gas and fuel) in these stages. Moreover, the statistical analysis provided 95% level of confidence intervals for the mean and the standard deviation very accurate which shows that using the mean inventory values from all the enterprises that were consulted within the same stage of the life cycle is a suitable method of working. Future users of the inventory may use the probability distributions obtained for calculating percentiles or other measures to assess their data.

Keywords Ceramic tile · Clay · Glaze · Life cycle assessment (LCA) · Life cycle inventory (LCI) · Statistical analysis

Responsible editor: Marzia Traverso

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1 Introduction

The aim of this paper is to conduct a Life Cycle Assessment (LCA) (ISO 14040-44 2006) study of ceramic tiles (single-fired glazed stoneware) in order to identify the stages that produce the greatest impact on the environment and the materials and/or processes that make the largest contribution to that impact. The life cycle is considered to be made

up of seven stages: (1) mining the clay, (2) atomising the clay, (3) production of frits and glazes, (4) production of ceramic tiles, (5) distribution, (6) installation and usage until the end of its useful life and finally (7) treatment as construction and demolition (C&D) waste.

The quality and credibility of the results of an LCA study depend largely on the quality of the data included in the Life Cycle Inventory (LCI) stage. This inventory must state, in a specific and reliable way, all the inputs in the form of material and energy resources and the outputs in the form of air emissions, emissions into water and soil, as well as the solid waste that is generated, in each of the stages of the life cycle of the system under study (ISO/TR 14048 2002).

Drawing up an LCI is the costliest task in an LCA study due to the large amounts of resources that have to be consumed (especially time) in order to obtain up-to-date and reliable information. To make this task easier, there are a number of public and private LCI databases that include inventories of specific materials and processes from different industrial sectors (Ecoinvent 2008; Idemat 2001; Franklin 1998; ELCD 2011; IVAM LCA 2005; etc.). However, none of them include inventory data that cover all the stages of the life cycle of a ceramic tile. Therefore, in order to apply the LCA methodology, first it is necessary to draw up an LCI that is specific to the ceramic tile sector and which applies geographically to Spain. This information will then be used to obtain the environmental indicators.

This paper is structured in the following way: section 2 presents a thorough review of the inventory data published in the literature and in LCI databases; section 3 shows the LCI and its impact analysis broken down into each of the stages under consideration; section 4 offers the results of the statistical study of the environmental indicators obtained and lastly, in section 5 findings are discussed and conclusions are presented.

2 Background

The harmonised conditions for the marketing of the construction products (COM 311 2008) establishes the need to design buildings that have a low impact on the quality of the environment throughout their entire life cycle, which includes their construction, use and demolition. Hence, it becomes necessary to assess the environmental behaviour of the different types of construction materials, which has given rise to LCA studies applied to different building materials. Asif et al. (2007) analysed construction materials that are typically used in dwelling homes such as wood, aluminium, glass, concrete and ceramic tiles; Rydh and Sun (2005) analysed both porous ceramics and ceramics, cement and concrete; Steve and Krieger (2007) studied electrical metallic tubing; Aguado et al. (2004), cement; Traverso et al. (2010), marble; Nicoletti et al. (2002) both marble and ceramic tiles; Koroneos and Dompros (2007), brick production, and so forth.

Inventory data directly related with ceramic tiles included in the literature and in LCI databases are generally scarce and mostly oriented towards a specific stage of their life cycle. Table 1 shows an extensive review of inventory data related with ceramic tiles published in the literature. The table shows the inputs (in the form of amounts of material and energy resources that are consumed) and the outputs (in the form of emissions) included in the inventories for each bibliographical reference. This information is shown for each of the sources and for each of the stages of the life cycle of ceramic tiles.

As far as LCI databases are concerned, only Ecoinvent (2008) and Idemat (2001) include inventory data about ceramic tiles in the category *construction materials*. The first adapts the data about Italian ceramic enterprises collected between 1998 and 2002 by Nicoletti et al. (2002) to the case of Switzerland. Idemat (2001) uses data from the Netherlands collected between 1990 and 1994. The extension database for construction materials included in Gabi (2010) also incorporates materials such as clay, concrete, bricks, etc. mainly refereed to Germany (2001–2008).

As regards inventories included in research publications and papers, some of the most significant contributions are those of Bovea et al. (2005, 2007, 2010) and Tikul and Srichandr (2010). The first include inventory data corresponding to the packaging process of tiles, extraction and commercialization of red clay or manufacture of ceramic tiles, respectively, with data from before the year 2006 and all of which are from only one company in each stage. Moreover, the stages of installing and maintaining the tiles or their management as C&D waste when they come to the end of their useful life are not included. Some specific data about installation and maintenance of the main floor coverings were reported by Nicoletti et al. (2001). Tikul and Srichandr (2010) included inventory data from a single enterprise in Thailand and the scope of their study was taken as being only the stage of manufacturing of the tile, while the mining and production of raw materials, distribution, use and end of life are therefore excluded from the study.

With regard to the inventory data that could be extracted indirectly from the application of Directive 61/EC (1996) and Directive 1/EC (2008) on Integrated Pollution Prevention Control to the ceramic tile sector, some of the most notable data are those provided by the reference document BREF (2007), which defines the best available techniques to be applied to this industrial sector and the emission limit values proposed in the integrated environmental authorisations granted to enterprises that manufacture ceramic tiles (Vázquez 2008). Emissions and natural gas consumption limits established in the environmental criteria of the European Ecolabel for hard floor coverings (Commission

Table 1 Inventory data related with the life cycle of ceramic tiles published in the literature

			Nicoletti et al. (2002)	Monfort et al. (2009)	Minguillón et al. (2009)	Tikul and Srichandr (2010)	Blasco et al. (1992)	Busani et al. (1995)	CD 607CE (2009) (European Ecolabel)	Ecoinvent (2008)	Idemat (2001)	Bovea et al. (2010)
A. Raw material extraction	Consumptions											
	Electricity (kWh/t raw mat.)	5.35E+1	–	–	–	–	–	–	–	–	6.04E+2	
	Fuel (MJ/t raw mat.)	9.78E+1	–	–	3.05E+4	–	–	–	2.97E+1	–	2.78E+4	
	Natural gas (MJ/t raw mat.)	–	–	–	–	–	–	–	–	–	–	
	Airborne emissions[a]											
	PM_{10} (kg/t raw mat.)	–	5.85E−1	1.07E+0	–	–	–	–	–	–	–	
B. Atomisation	Consumptions											
	Electricity (kWh/t treated)	5.50E+1	–	–	1.72E+3	–	–	–	–	–	–	
	Fuel (MJ/t treated)	2.08E+3	–	–	5.86E+3	–	–	–	–	–	1.08E+1	
	Natural gas (MJ/t treated)	–	–	–	1.80E+3	–	–	–	–	–	1.92E+3	
	Airborne emissions											
	PM_{10}	(kg/t treated)	–	3.70E−1	7.35E+0	2.58E−1	1.75E+1–2.28E+1	1.78E+1–2.28E+2	–	–	–	9.67E−1
	CO_2		–	–	–	4.63E+2	–	7.00E+1–9.00E+1	–	–	–	–
	NO_x		–	–	–	3.35E−1	–	–	–	–	–	–
	SO_x		–	–	–	1.65E+0	–	–	–	–	–	–
	F		–	–	–	8.14E−7	–	–	–	–	–	–
	Pb		–	–	–	1.15E−3	–	–	–	–	–	–
	CO		–	–	–	4.78E−2	–	–	–	–	–	–
	Cd		–	–	–	8.14E−7	–	–	–	–	–	–
	Hg		–	–	–	2.36E−5	–	–	–	–	–	–
	Cu		–	–	–	6.52E−5	–	–	–	–	–	–
	Cr		–	–	–	1.30E−4	–	–	–	–	–	–
C. Glaze production	Consumptions											
	Electricity (kWh/t glaze)	2.59E+2	–	–	1.60E+3	–	–	–	–	–	–	
	Fuel (MJ/t glaze)	1.90E+1	–	–	1.28E+4	–	–	–	–	–	1.82E−3	
	Natural gas (MJ/t glaze)	2.54E+3	–	–	0.00E+0	–	–	–	–	–	4.63E+3	
	Airborne emissions											
	PM_{10}	(kg/t glaze)	–	–	4.42E+0	–	6.50E+0	7.45E+0–7.68E+0	–	–	–	3.73E+0
	Cl		–	–	–	–	6.37E−1	6.86E−1	–	–	–	–
	NO2		–	–	–	–	1.04E+1	1.12E+1	–	–	–	–
	SO2		–	–	–	–	9.49E−1	1.02E+0	–	–	–	4.44E−2

Table 1 (continued)

			Nicoletti et al. (2002)	Monfort et al. (2009)	Minguillón et al. (2009)	Tikul and Srichandr (2010)	Blasco et al. (1992)	Busani et al. (1995)	CD 607CE (2009) (European Ecolabel)	Ecoinvent (2008)	Idemat (2001)	Bovea et al. (2010)
	NH3		–	–	–	–	1.30E−3	1.40E−3	–	–	–	–
	B		–	–	–	–	3.25E−1	3.50E−1	–	–	–	–
	F		–	–	–	–	5.00E−2	5.00E−2	–	–	–	1.15E−1
	Pb		–	–	–	–	1.00E+0	1.00E+0	–	–	–	–
	CO2		–	–	–	–	–	5.75E+2–8.00E+2	–	–	–	–
	As		–	–	–	–	–	1.43E-1	–	–	–	–
D. Tile production[b]	Consumptions											
	Electricity (kWh/t tile)	8.59E+1	–	–	2.34E+2	–	–	–	–	3.13E+2	–	
	Fuel (MJ/t tile)	–	–	–	9.34E+2	–	–	–	–	–	–	
	Natural gas (MJ/t tile)	3.58E+3	–	–	4.71E+3	–	–	–	3.50E+3	5.87E+3	–	
	Airborne emissions											
	PM_{10}	(kg/t tile)	–	–	1.79E+0	3.01E−1	–	8.39E−1–1.03E+0	8.39E-1 - 1.03E+0	1.16E−2	8.71E+0	5.70E−2
	Cl		–	–	–	–	–	4.27E−1	4.27E−1	–	–	5.00E−2
	NO_x		–	–	–	3.44E−1	–	4.27E−1	4.27E−1	1.45E-1	–	4.00E−1
	SO_x		–	–	–	1.10E+0	–	5.95E−1	5.95E−1	8.71E-2	–	3.30E−1
	NH3		–	–	–	–	–	5.34E−3	5.34E−3	–	–	–
	B		–	–	–	–	–	2.52E−2	2.52E−2	–	–	–
	F		–	–	–	8.32E−7	–	1.08E−2–3.08E−2	1.15E−2–3.08E−2	1.16E−2	–	1.50E−1
	Pb		–	–	–	9.16E−4	–	4.22E−3–1.15E−2	3.62E−3–1.15E−2	–	–	–
	CO2		–	–	–	9.38E+2	3.05E+2	–	1.36E+1–2.02E+1	–	–	
	As		–	–	–	–	–	–	2.00E−4	–	–	–
	CO		–	–	–	2.45E−2	–	–	–	–	–	7.00E−1
E. C&D	Consumptions											
	Electricity (kWh/t tile)	–	–	–	–	–	–	–	–	–	–	
	Fuel (MJ/t tile)	1.61E+2	–	–	–	–	–	–	–	–	–	

C&D construction and demolition

[a] Data for raw material extraction emissions are not inventory data but process information

[b] To unify units, it has been considered 1 m^2 of ceramic tile, according to quantities reported in Fig. 1

Decision 607/CE 2009) can also be useful as a guide to drawing up an inventory of the process of manufacturing ceramic tiles in Europe.

Given the discrepancy among the data shown in Table 1, the very low data obtained from Spanish tile facilities and the age of some of the information, as well as the lack of data concerning stages such as use and end of life (not only landfilling but recycling), it can be concluded that an up-to-date and adapted to the Spanish situation LCI for ceramic tiles needs to be drawn up, since almost the 40% of the European ceramic tiles is produced in Spain (ASCER 2009). At the same time, it should also cover all the stages of the life cycle of ceramic tiles, from the mining of the raw materials to their management as C&D waste.

3 Application of the LCA methodology

3.1 Definition of aims and scope

The main aim of this study is to conduct an environmental analysis of the life cycle of ceramic tiles by applying the LCA methodology in order to identify the stages of the life cycle and the processes/materials that make the greatest contribution to the environmental impact of this product. To this end, and as concluded in the previous section, a specific LCI was developed from the data collected directly from Spanish enterprises involved in each of the stages of the life cycle of ceramic tiles.

The scope of the study can be observed in Fig. 1, which illustrates the flows of inputs (raw material, energy, fuel, water, etc.) and outputs (airborne emissions, emissions into water and soil, as well as solid waste) produced throughout the seven stages that go to make up the life cycle of the tile. An examination of the machinery and infrastructures required at each of the stages lies beyond the scope of this study. The system of the analysis is the single-fired ceramic tile with a density of 17.23 kg/m^2 (average density). The function of the system is to ensure a proper cover of a building walls and floors. The functional unit chosen is 1 m^2 of ceramic tile over a period of 20 years [average life of tiles according to Carani et al. (1997)].

3.2 Life cycle inventory

The life cycle inventory states, in a specific and reliable way, all the inputs and outputs of materials, water, energy, airborne emissions, emissions into water and soil, as well as solid waste at each stage of the life cycle of ceramic tiles, from the mining of the raw materials to the management of the tiles as C&D waste at the end of their useful life. As stated in ISO/TR 14048 (2002), information was collected by quantifying the input and output flows of each of the seven stages considered in the life cycle of the ceramic tile. To do so, data were gathered from 35 Spanish enterprises covering the five industrial sectors involved, as shown in Table 2, together with the overall production capacity of the plants considered.

The procedure that was followed to collect and process data in each of the stages was the following:

– Collection of annual data about inputs (annual consumption of materials, water, electricity, natural gas, fuel, etc.) and outputs (emissions into the air, water and soil, and hazardous and non-hazardous waste, each with their corresponding treatment).

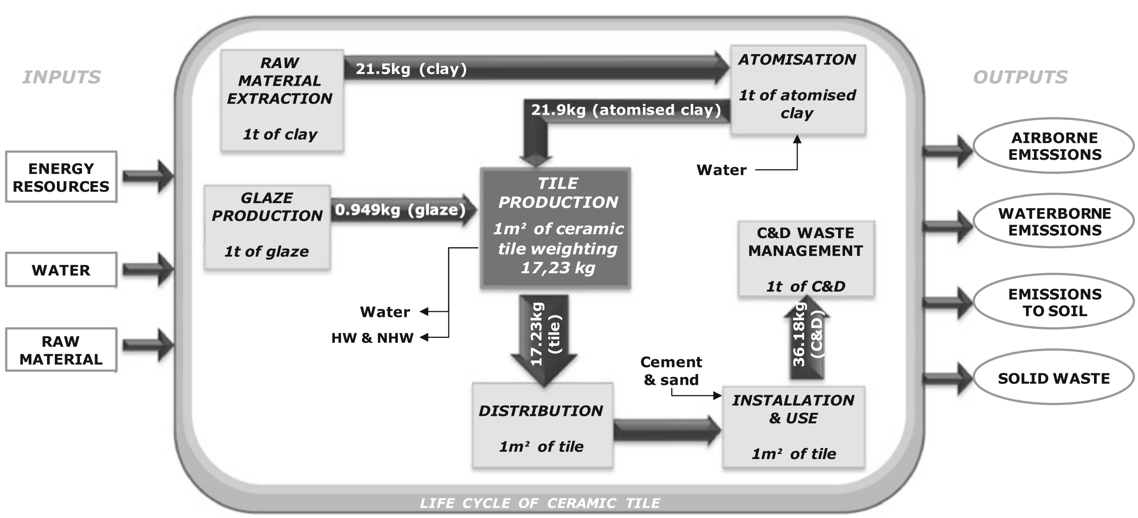


Fig. 1 Life cycle of ceramic tiles, inputs, outputs, functional units and main intermediate product flows

Table 2 List of number and annual production of enterprises that data were obtained from

Industrial sector	Number of firms	Annual production capacities
Mining sector	3	3,313,025 t of extracted earth
Atomising plants	4	2,055,039 t of atomised earth
Frits and glazes manufacturers	5	299,629 t of glaze produced
Tile factories	20	97,650,480 m^2 of tiles produced
C&D waste disposal contractors	3	1,149,450 t of C&D waste

C&D construction and demolition

– Relating data to unit processes to the functional unit contemplated for each stage, by applying some criteria such as cause-and-effect relation of diesel consumption according to the amount of diesel consumed by the machinery, direct relation of electricity consumption according to the power produced by the machinery in each stage, etc.
– Modelling of the inventories in SimaPro 7.3 (2010), taking the Ecoinvent (2008) database as a reference to configure the inventory of minority materials, fuel and electricity. These secondary data were adjusted as much as possible to each particular case, by adapting the electric mix to that of Spain for the year 2009 (REE 2010), to the distances and to the means of transport.

Table 3 shows a comparison of the mean energy consumptions, as well as the main airborne emissions, waste generated and input and output flows of water for the five stages shown in Table 2. All data were related to the production of 1 m^2 of ceramic tile, taking into account the amounts of each raw material defined in Fig. 1. For the sake of confidentiality, rather than giving individual data for each enterprise, the mean data collected for each stage of the life cycle are shown.

Table 3 Inventory data for each stage of the life cycle of 1 m^2 of ceramic tile

	Mine	Atomising plant	Glaze plants	Tile factories	Distribution	Installation and use	C&D waste
Non-renewable energy							
Electricity (kWh/m^2)	6.16E-03	−2.59E+00	9.99E−02	1.95E+00	0	7.88E−02	5.03E−02
Diesel (L/m^2)	2.00E-02	6.86E−03	1.26E−03	9.55E−03	5.07E−01	0	2.46E−02
Natural gas (kWh/m^2)	0	1.58E+01	1.29E+00	1.83E+01	0	0	0
Airborne emissions kg/m^2							
PM_{10}	6.67E−10	4.65E−03	1.37E−04	2.59E−03	–	–	–
NO_x	0	1.35E−02	2.15E−03	5.25E−03	–	–	–
SO_x	9.90E−08	3.30E−03	2.40E−04	4.19E−03	–	–	–
CO	1.86E−05	2.12E−03	7.72E−05	9.90E−03	–	–	–
HF	0	3.69E−04	6.04E−06	1.80E−05	–	–	–
Pb	0	0	2.59E−05	3.25E−04	–	–	–
As	0	0	5.30E−09	5.48E−08	–	–	–
Hg	0	0	4.41E−09	3.49E−08	–	–	–
Cu	0	0	2.39E−07	2.16E−07	–	–	–
Cr	0	0	6.32E−08	1.46E−07	–	–	–
Hazardous and non-hazardous waste (kg/m^2)							
HW	5.46E−04	6.23E−04	3.90E−02	2.78E−03	–	–	0
NHW	8.82E−04	1.03E−02	2.17E−03	2.86E+00	–	–	4.15E+00
Water inputs and outputs (m^3/ m^2)							
Incoming water	5.39E−04	1.10E−02	7.25E−04	5.74E−03	–	–	0
Outgoing water	0	1.09E−03	1.84E−04	4.44E−03	–	–	0

HW hazardous waste, *NHW* non-hazardous waste, *C&D* construction and demolition

Intermediate product transports were considered in each stage assuming a distance between facilities up to 20 km and a large lorry with load capacity over 32 t as the transport vehicle.

In the distribution stage, the percentages of national sales and exports shown in Table 4 (ASCER 2009) were taken into account together with the means of transport and distances reported.

The technique considered in the stage of installing the tiles is the so-called thick layer method. That is to say, it is assumed that the adhesive material used to fix the tile to the floor is a mixture of 15% cement and 85% sand and that a 3-cm layer of cement adhesive is used to stick a 1-cm thick ceramic floor tile to the structural element or base.

Regarding the use and conservation of the ceramic tile, it is assumed that maintenance operations consist of first cleaning after the installing operation with an acid detergent (0.005 L/$m^2 \times 20$ years) in order to remove adhesive residues from the tile surface, and an ordinary cleaning which consists of a daily dusting and a weekly cleaning with a neutral detergent (1.8 L/$m^2 \times 20$ years) (Nicoletti et al. 2001). Because of the use of a broom for dusting and the low quantities of detergents needed for cleaning tiles, any significant environmental impact is assumed for the use phase.

Finally, for the end-of-life of the tile, its treatment as a C&D waste has been assumed, including transport to treatment facility. The transport distance considered was 100 km (average distance between Spanish cities and their C&D treatment facilities).

3.3 Impact assessment

Once the inventory that covers the whole life cycle of the ceramic tile had been drawn up, the environmental impact assessment was performed. Following the methodology proposed by the ISO 14040-44 (2006) standard, environmental indicators were obtained for the six different impact categories that were chosen (Table 5). The characterisation factors applied to each impact category were those put forward by the CML 2001 method (Frischknecht et al. 2007).

Figure 2 represents the contributions that each of the enterprises that were analysed made to each impact category throughout the life cycle of 1 m^2 of ceramic tile; that is to say, the analysis shows the impact that each enterprise generates while producing the material needed to manufacture that square metre, i.e. in manufacturing it, distributing it, installing it or disposing of it as waste.

Table 4 Data considered for the distribution stage

	% of national sales and exports	Average distance (km)	Type of transport
National	50	500	32-t trailers
International			
Rest of Europe	33.75	2,000	32-t trailers
America	5.05	7,000	Ocean-going cargo ships
Middle East	5.55	4,000	Ocean-going cargo ships
East and Southeast Asia	1.35	20,000	Ocean-going cargo ships
Africa	3.9	5,000	Ocean-going cargo ships
Oceania	0.4	20,000	Ocean-going cargo ships

Table 5 Impact categories, category indicators and characterization models

Impact categories	Category indicators	Characterization models
Acidification potential	kg SO_2 eq	CML2001
Eutrophication potential	kg PO_4 eq	CML2001
Global warming potential	kg CO_2 eq	CML2001
Ozone layer depletion potential	kg CFC–11 eq	CML2001
Photochemical oxidation potential	kg C_2H_4	CML2001
Human toxicity potential	kg 1.4–DB eq	CML2001

4 Statistical analysis

The statistical analysis performed in this study is used as a tool that allows making inferences about the real and global environmental behaviour of the life cycle of the ceramic tile by analysing the sample.

The statistical analysis is divided into three stages:

a. Generation of the sample data by combining the environmental results obtained for each of the enterprises that were analysed.
b. Calculating descriptive measures for the six different impact categories and carrying out goodness-of-fit tests in order to determine what probability distribution provides a best fit to the environmental data.
c. Determining the confidence intervals for the mean and the standard deviation of the environmental data obtained for each impact category.

To perform all the statistical analyses, the statistical package STATGRAPHICS was used.[1]

[1] Statgraphics is distributed by StatPoint Technologies, Inc.

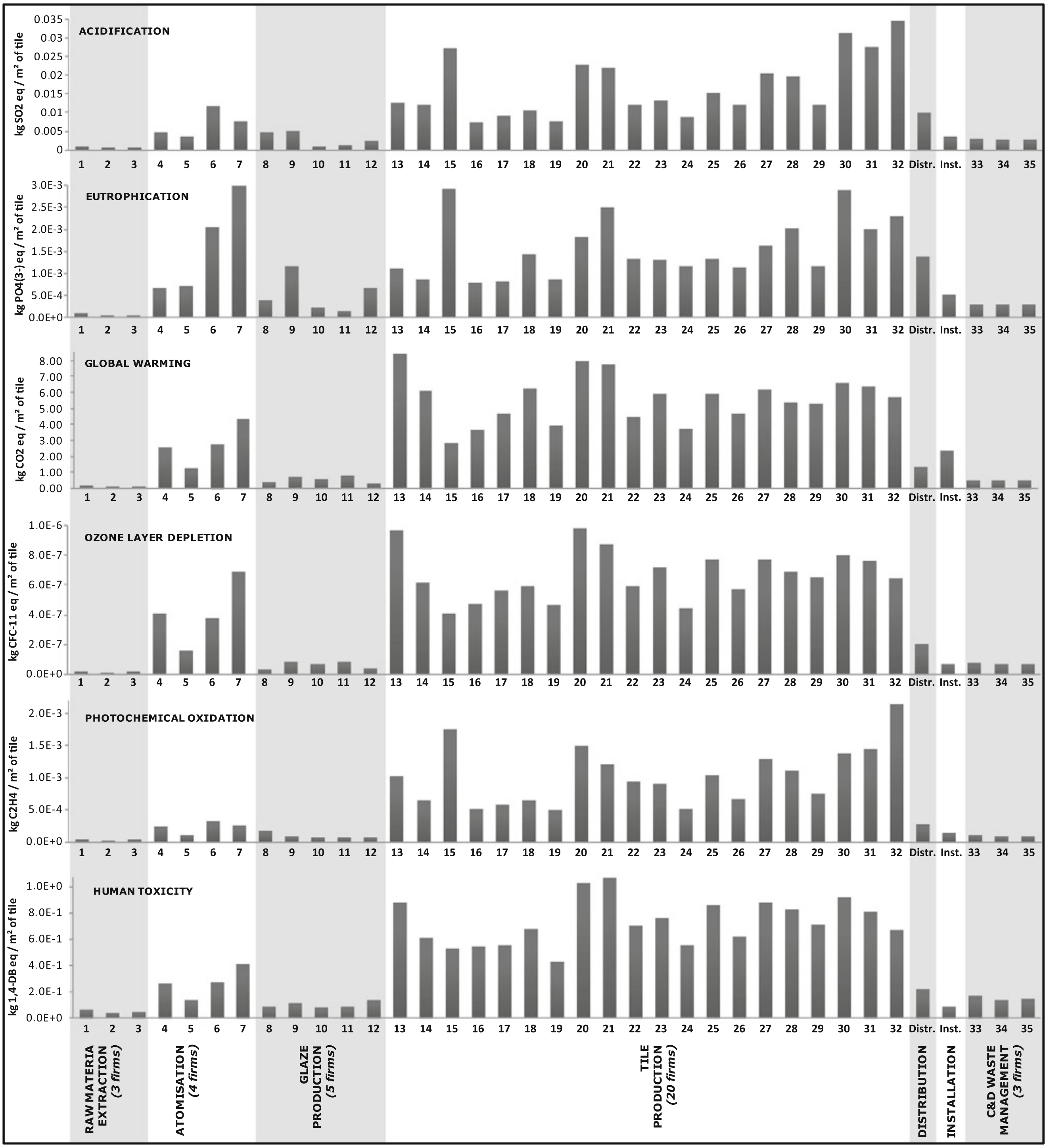


Fig. 2 Environmental impacts of each of the enterprises that were analysed (general functional unit 1 m^2 of ceramic tile)

4.1 Generation of statistical sample data

Figure 3 shows how the environmental results obtained for each of the 35 enterprises in the analysis were combined. This combination of enterprises gave rise to 3,600 possible impacts that the entire life cycle of the tile produces for each category that was analysed. In other words, altogether there were 21,600 environmental data items grouped in 6 samples each containing 3,600 items of data.

4.2 Testing goodness of fit

Previously to formal statistical test, descriptive measures for describing central tendency and dispersion were

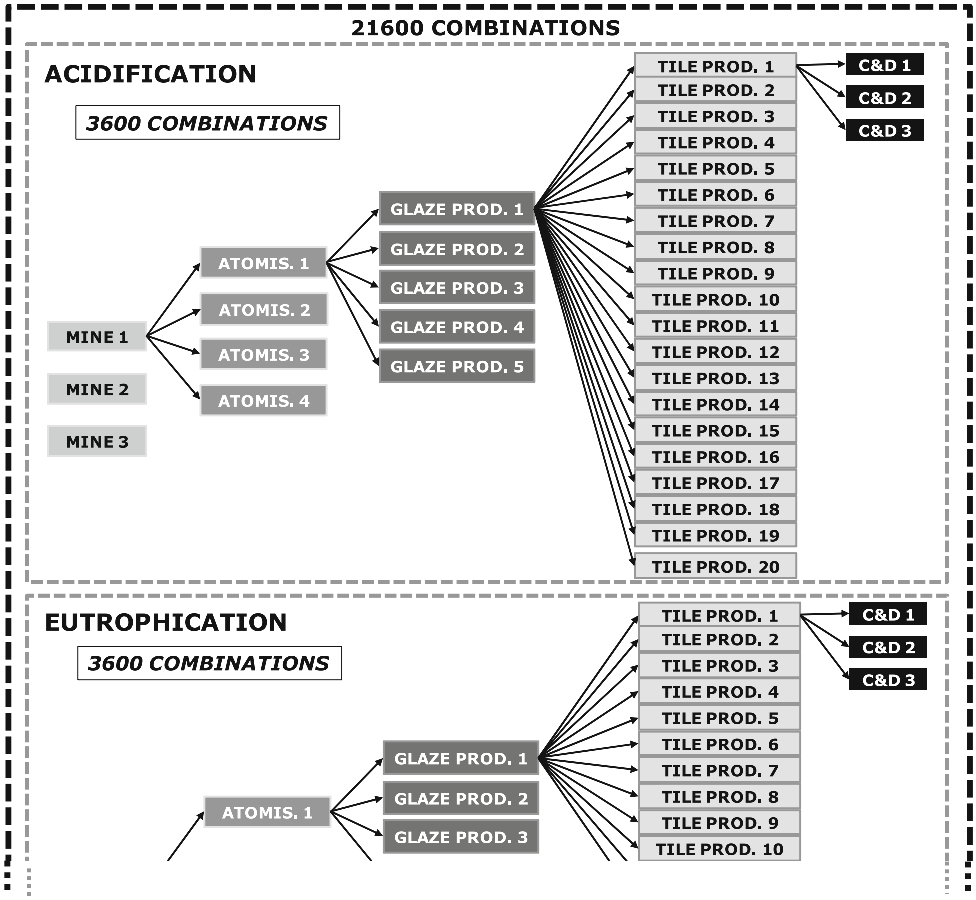


Fig. 3 Data obtained by combining the 35 enterprises that were analysed for each of the six impact categories

obtained from the sample data; then, the density functions for each impact category were estimated and represented graphically. These measures and plots give a first description of data and they provide a tool for a first guessing about what kind of probability model could fit to the data set. The left-hand column of Table 6 contains the estimated density functions and the column on the right shows the parameters of the measures of central tendency and dispersion that were calculated (maximum and minimum value, mean and standard deviation). Regarding these plots, the three most common probability models for inventory data will be used to try to fit the collected data: normal, lognormal and triangular.

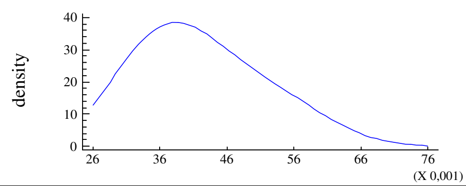
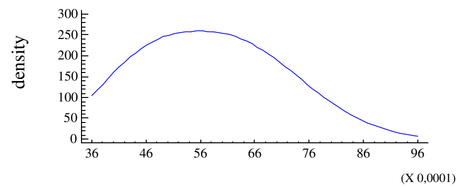
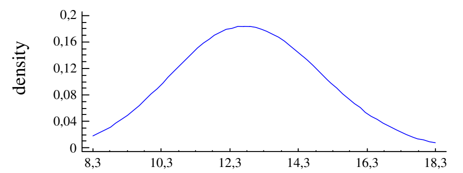
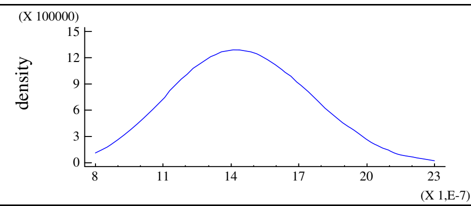
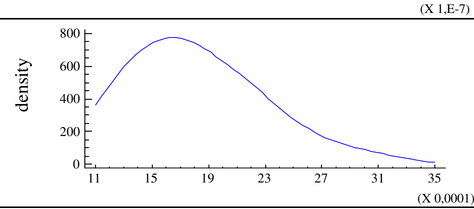
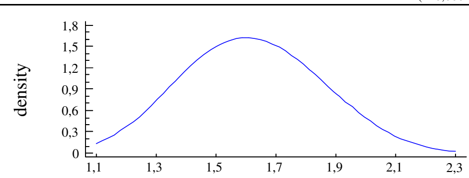
After this first descriptive study, two kind of statistical tools were used to determine the suitability of each chosen model and the quality of fit to the six samples that were analysed, they are:

- *A graphical procedure*: The quantile–quantile plot (Q-Q plot) which represents the discrepancy that exists between the ordered values of the sample and the corresponding theoretical quantiles of the proposed model.
- *Formal tests for goodness of fit*: In particular, Kolmogorov–Smirnov and Anderson–Darling tests compare the frequencies observed in a sample with the theoretical frequencies under the distribution that is being tested. Therefore, their *p* value determines quantitatively whether there is a possibility of the sample behaving in accordance with a certain model or not. If small *p* values are obtained (below 0.05 or 0.01), it is said that there is evidence that the observed data do not come from the hypothesized distribution.

To conduct these tests, the size of the sample was previously reduced by randomly selecting 200 of the 3,600 data items. The reason for this is that so large sample size makes the power of the test (the probability of correctly rejecting the null hypothesis) so high than it is difficult to adjust the results to a particular statistical distribution. Even with trivial differences, the null hypothesis would always be rejected, even when it turns out, in an important sense, to be an excellent approximation to the data (Hill and Lewicki 2007).

Table 7 shows, for each indicator, the Q-Q plot for the model that is found to have the best fit. This fit is tested by applying the two goodness-of-fit tests (right hand column of Table 7).

Table 6 Characteristic parameters and density functions

Acidification		Units: **kg SO_2 eq.** Min. = 2,85E-02 Max. = 6,87E-02 Mean = 4,38E-02 St. deviation = 8,87E-03
Eutrophication		Units: **kg PO_4^{3-} eq.** Min. = 3,80E-03 Max. = 9,35E-03 Mean = 5,94E-03 St. deviation= 1,23E-03
Global warming		Units: **kg CO_2 eq.** Min. = 8,70E+00 Max. = 1,80E+01 Mean = 1,32E+01 S. deviation = 1,82E+00
Ozone layer depletion		Units: **kg CFC-11 eq.** Min. = 9,48E-07 Max. = 2,12E-06 Mean = 1,50E-06 St. deviation = 2,49E-07
Photochemical oxidation		Units: **kg C_2H_4 eq.** Min. = 1,16E-03 Max. = 3,16E-03 Mean = 1,87E-03 St. deviation = 4,52E-04
Human toxicity		Units: **kg 1,4-DB eq.** Min. = 1,13E+00 Max. = 2,16E+00 Mean = 1,62E+00 St. deviation = 1,96E-01

From the goodness-of-fit p values, it is clearly accepted that "eutrophication", "acidification" and "human toxicity" fit a lognormal distribution meanwhile "photochemical oxidation" fits a triangular, since the p values are higher than 0.1 for the three variables. In contrast, the other two variables are not so clearly defined: for "ozone layer depletion" and "global warming", the normal hypothesis would be clearly accepted with the Kolmogorov–Smirnov test, whereas with the other test it would be accepted only for p values of 0.05 and 0.01, respectively.

4.3 Confidence intervals

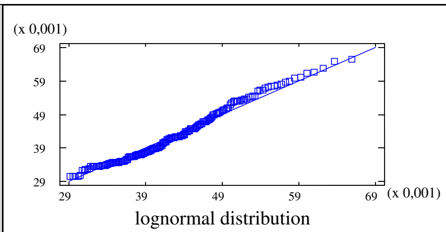
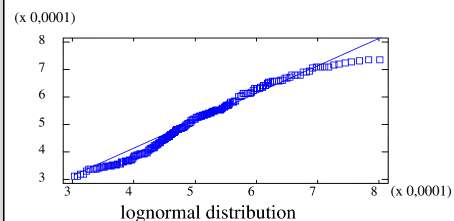
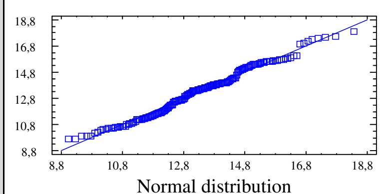
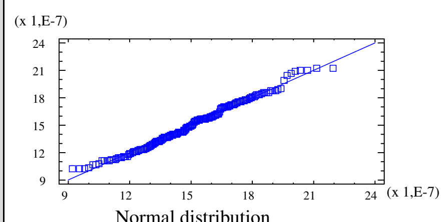
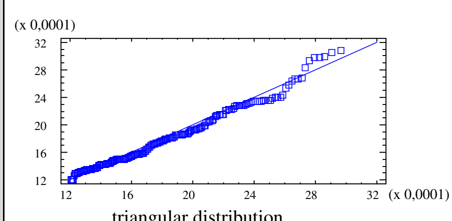
To complete the descriptive study conducted at the beginning of the previous paragraph, confidence intervals for the mean and standard deviation were calculated. These intervals are calculated from the sample and give an estimate of the real mean and standard deviation with an accurace given by the selected level of confidence. They are calculated for the total contributions for each impact category.

Table 8 shows the confidence intervals calculated at a 95% confidence level for the six impact categories analysed. The large sample size has produced very close intervals, that is to say estimation is very accurate.

5 Discussion and conclusions

From the results shown in Fig. 2, it can be seen that it is the ceramic tile-manufacturing enterprises, followed by the atomising plants, which make the greatest contribution to

Table 7 Graphs showing the Q-Q plots and goodness-of-fit test p values for the six samples

Acidification		***"Lognormal"*** P-values from Goodness-of-Fit tests: K-S: 0,145131 Anderson-Darling: >= 0.10
Eutrophication		***"Lognormal"*** P-values from Goodness-of-Fit tests: K-S: 0,167166 Anderson-Darling: >= 0.10
Global warming		***"Normal"*** P-values from Goodness-of-Fit tests: K-S: 0,518611 Anderson-Darling: between 0,01 and 0,05
Ozone layer depletion		***"Normal"*** P-values from Goodness-of-Fit tests: K-S: 0,590907 Anderson-Darling: between 0,05 and 0,01
Photochemical oxidation		***"Triangular"*** P-values from Goodness-of-Fit tests: K-S: 0,19182 Anderson-Darling: >= 0.10

the environmental impact of the life cycle of ceramic tiles. This is mainly due to the high quantities of electricity and natural gas (see Table 3) required by the processes involved in these stages.

If each stage of the life cycle is examined in more detail, the contribution to the impact from mining the red clay is essentially due to the consumption of fuel needed to operate the earth-moving machinery (0.93 L/t of clay extracted). Atomising plants consume large amounts of natural gas (726.58 kWh/t of atomised clay) and electricity (47.94 kWh/t of atomised clay), the impact of which is offset by the incorporation of cogeneration systems in their facilities which produce a mean of 166.21 kWh/t of atomised clay. The production of frits and glazes stands out for being the stage in the life cycle that generates the greatest amounts of hazardous waste (41.13 kg/t of frits and glass produced). Moreover, this stage requires high levels of water consumption in the melting process (520 L/t of frits and glass produced). In spite of this, as can be seen from Table 3, in the process of manufacturing ceramic tiles, the atomisation of clay is the phase with the highest incorporation of water (11 L/m^2). The stage in which the

Table 8 Confidence intervals of the mean and standard deviation for each impact category

Acidification	Mean= [4,35E-02 ; 4,41E-02] Standard deviation= [8,67E-03 ; 9,08E-03]
Eutrophication	Mean= [5,90E-03 ; 5,98E-03] Standard deviation= [1,20E-03 ; 1,26E-03]
Global warming	Mean= [1,31E+01 ; 1,33E+01] Standard deviation= [1,78E+00 ; 1,86E+00]
Ozone layer depletion	Mean= [1,49E-06 ; 1,50E-06] Standard deviation= [2,44E-07 ; 2,55E-07]
Photochemical oxidation	Mean= [1,85E-03 ; 1,88E-03] Standard deviation=[4,42E-04 ; 4,63E-04]
Human toxicity	Mean= [1,61E+00 ; 1,63E+00] Standard deviation=[1,92E-01 ; 2,01E-01]

ceramic tile is actually produced is the one that generates the greatest impact for all the impact categories. This is chiefly due to the consumption of natural gas needed in the drying and firing processes (7.04 kWh/m^2 and 10.86 kWh/m^2) besides the airborne emissions of CO, NO_x and SO_x (see Table 3) that come mainly from these two processes. In this context, firing and drying lines play a significant role in the environmental impact of tiles. Therefore, the implementation of best available techniques in these processes is specially recommended in order to improve the sustainability of the whole life cycle of ceramic tiles. Distribution is a stage to be borne in mind, due to the fact that 50% of the production is exported, which means that, depending on the distance to the destination, it can be one of the most predominant stages from the environmental point of view. The contribution made by the tile installation stage is a result of the process of manufacturing cement and its transport to areas where tiles are installed (transport distances up to 40 km), since any impact during its use has been neglected. Finally, it must be pointed out that, unlike most of the studies in the literature review, the stage involving management of the tile as C&D waste for its recycling was included, and results show that it is slightly significant in the life cycle of ceramic tiles. C&D waste (tiles and adhesive materials) transport to treatment facilities is the origin of the most contribution made in this stage.

A distribution model for the environmental behaviour of the life cycle of ceramic tiles for each impact category has been found; this model has been developed by considering the different contributions of each company analysed. Additionally, the obtained confident intervals for the mean and the standard deviation of the total contributions produced, both calculated at a confidence level of 95%, are very accurate because of the large sample size. Both results are powerful tools for the use of the inventory in future environmental analysis. The fact that the intervals are as precise shows that the use of these mean values is a feasible way to work. Future users of the inventory may use the probability distributions obtained for calculating percentiles or other measures to assess their data.

Acknowledgements This work was made possible through the funding from the Spanish Ministry of Science and Innovation, the Generalitat Valenciana and the collaboration of the firms involved.

References

Aguado A, Josa A, Cardim A (2004) Strengths and weaknesses of the inventory of cement for use in life cycle assessment (LCA). Bull of the Spanish Soc of Ceram and Glass 43(2):15–24

ASCER (2009) Development of exports of Spanish ceramic tile industry, year 2008. (Press release March 18, 2009)

Asif M, Muneer T, Kelley R (2007) Life cycle assessment: a case study of a dwelling home in Scotland. Build Environ 42:1391–1394

Blasco A, Escardino A, Busani G, Montort E, Amorós JL, Enrique J, Beltrán V, Negre P (1992) Treatment of gaseous emissions, liquid effluents and solid waste from the ceramic industry. AICE-ITC e IMPIVA, Castellón

Bovea MD, Serrano J, Bruscas GM, Gallardo A (2005) Application of life cycle assessment to improve the environmental performance of a ceramic tile. Packag Syst, Packag Technol and Science 19:83–95

Bovea MD, Saura U, Ferrero JL, Giner J (2007) Cradle-to-gate study of red clay for use in the ceramic industry. Int J Life Cycle Assess 12(6):439–447

Bovea MD, Díaz-Albo E, Gallardo A, Colomer FJ, Serrano J (2010) Environmental performance of ceramic tiles: improvement proposals. Mater Design 31:35–41

BREF (2007) Reference document on Best Available Techniques (BAT) in the ceramic manufacturing industry. European Commission, Institute for Prospective Technological Studies, Sevilla

Busani G, Palmonari C, Timellini G (1995) Piastrelle ceramiche & Ambiente. Edi.cer, S.p.a., Sassuolo, Italia

Carani G, Palmonari C, Timellini G (1997) Flooring material costs. Ceramica Acta 6, in Italian

COM 311 (2008) Proposal for a regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of the construction products

Commission Decision 607/CE (2009) of 9 July, concerning establishing the ecological criteria for the award of the EU Ecolabel to Hard Coverings (HC)s

Directive 1/EC (2008) of the European Parliament and the Council, of 15 January, concerning integrated pollution prevention and control

Directive 61/EC (1996) of the European Parliament and the Council, of 24 September, concerning integrated pollution prevention and control

Ecoinvent v2 (2008) The life cycle inventory data version 2. Swiss Centre for Life Cycle Inventories

Franklin (1998) USA LCI database documentation. Franklin Associates, Prairie Village

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Margni M, Nemecek T, Spielmann M (2007) Implementation of Life Cycle Impact Assessment Methods: data v2.0. Ecoinvent report No. 3, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland

Gabi (2010) Gabi software. PE International, Leinfelden-Echterdingen, Germany. (http://www.gabi-software.com/support/gabi/gabi-lci-documentation/data-sets-by-database-modules/extension-databases/xiv-construction-materials/)

Hill T, Lewicki P (2007) Statistics methods and applications. StatSoft, Tulsa

Idemat (2001) Delft University of Technology. The Netherlands

ELCD Core Database version II (2011) http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm

ISO 14040 (2006) Environmental management–Life Cycle Assessment–principles and framework. European Committee for Standardization (CEN)

ISO 14044 (2006) Environmental management–Life Cycle Assessment–requirements and guidelines. European Committee for Standardization (CEN)

ISO/TR 14048 (2002) Environmental management–Life Cycle Assessment–data documentation format. European Committee for Standardization (CEN)

IVAM LCA Data 2.0 (2005) IVAM Environmental Research. Amsterdam, The Netherlands

Koroneos C, Dompros A (2007) Environmental assessment of brick production in Greece. Build Environ 42:2114–2123

Minguillón MC, Monfort E, Querol X, Alastuey A, Celades I (2009) Effect of ceramic industrial particulate emission control on key components of ambient PM_{10}. J Environ Manage 90:2558–2567

Monfort E, Celades I, Sanfelix V, Gomar S, Lopez JL, Calpe V (2009) Estimation of diffuse emissions of PM10 and performance of BAT in the ceramic industry. Bull of the Spanish Soc of Ceram and Glass 48(1):15–24

Nicoletti GM, Notarnicola B, Tassielli G (2001) Products for the flooring maintenance: a comparison from an environmental point of view. In: Butijn CAA, Groot-Marcus JP, Van Der Linden M, Steenbekkers LPA, Terpstra PMJ (eds) Changes at the other end of the chain. Vol. 1, pp 369–380. Shaker Publishing, Maastricht, Netherlands. Proceedings of the European IFHE Congress “Changes at the other end of the chain”, Wageningen, 17–18 May 2001

Nicoletti GM, Notarnicola B, Tassielli G (2002) Comparative life cycle assessment of flooring materials: ceramic versus marble tiles. J Clean Prod 10(3):283–296

REE (2010) Red Eléctrica Española, annual report 2009 (in Spanish)

Rydh CJ, Sun M (2005) Life cycle inventory data for materials grouped according to environmental and material properties. J Clean Prod 13:1258–1268

Simapro 7.3 (2010) PRé Consultants B.V. Amersfoort, The Netherlands

Steve B, Krieger T (2007) Evaluating literature life cycle data: case study for electrical metallic tubing. DuPont Engineering Research and Technology. Reference Document on InLCA/LCM 2007 Conference Proceedings

Tikul N, Srichandr P (2010) Assessing the environmental impact of ceramic tile production in Thailand. J Ceram Soc Jpn 118 (10):887–894

Traverso M, Rizzo G, Finkbeiner M (2010) Environmental performance of building materials: life cycle assessment of a typical Sicilian marble. Int J Life Cycle Assess 15:104–114

Vázquez V (2008) Methodology for calculating emission limit values in integrated environmental authorisation. IX National Environmental Congress, Sustainable Development Summit, Madrid